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CONTENTS

Page

Studies in Interior Lighting, by J. M. Waldram, B.Sc., *(Fellow)* - 95

Additions to the List of Members - 134

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# Studies in Interior Lighting

By J. M. WALDRAM, B.Sc. (*Fellow*).


## Summary

The mechanism of interior lighting has been recently discussed in a Report of a Committee of the National Illumination Committee. The present paper records studies on three aspects of interior lighting: Adaptation, Revealing of Form and Texture, and Emphasis. It is proposed that effects of Adaptation should be taken into account in lighting calculations and values of Apparent Brightness used, for it is shown that figures of apparent brightness accord much better with experience than figures of absolute luminance, and explain anomalies which are found with absolute figures.

A new method of calculation is outlined, whereby the effects of interreflection can be found very simply without complex theory and by means suitable for day-to-day work, so that the installation can be designed from a specification of apparent brightness distribution.

The mechanism of the revealing of form and texture is discussed. Apparatus for the quantitative and systematic study of modelling and shadow are described; modelling indices and methods of portraying modelling capability of the lighting are proposed. Results in interiors of different types are given.

Emphasis is a more subtle effect than modelling and does not lend itself so well to quantitative study; it is discussed qualitatively and more briefly.

The techniques of experimental study of complete interiors are described and further general observations recorded. The effects of the factors discussed upon the lighting design for interiors are considered and possible techniques outlined. An appendix gives definitions of special terms used in the paper; a second appendix discusses techniques used, and a third describes the new method of calculation.


## (1) Introduction

There has been a revolution in thought in interior lighting in the past eight years. A movement is taking place, forecast 23 years ago or more[1], and "Illuminating Engineering" is beginning to give place to "Brightness Engineering," at least on the other side of the Atlantic. In this, interior lighting is following the lead of street lighting, which became in England a matter of Brightness Engineering in about 1934.

It is not clear exactly what is meant in the United States by Brightness Engineering, and in the author's view it is an inadequate term. The present-day trends of thought have been discussed in a Report of a Sub-Committee of the British National Committee[2], which was recently published in the Transactions of this Society; the title of that Report—"The Design of the Visual Field"—is perhaps more adequate than "Brightness Engineering." In that Report it is pointed out that recently the conception of interior lighting has progressed far beyond the provision of illumination on a working plane, to include decoration, brightness distributions, comfort, emphasis, modelling and other matters. The Report surveys the whole field, outlines the procedure to which we might come, and indicates the gaps in our knowledge. The present paper is concerned with contributions to some of those gaps, and it should be read with the Report in mind.

One section of that Report must be repeated here in abridged form, in order to indicate the place of the work to be reported. It was pointed out that when light is released in an interior, the following processes occur :—

(i) Interior surfaces are illuminated and interreflection takes place between them,

Communications from the Staff of the Research Laboratories of The General Electric Co., Ltd., Wembley. The manuscript of this paper was first received on November 6, 1953, and in revised form on November 30, 1953. The paper was presented at a meeting of the Society held in London on January 12, 1954.

and a luminance pattern is consequently built up. This pattern is a function of the interior reflection properties as much as of the light distribution.

(ii) The luminance pattern is the function of the lighting in virtue of which users see objects in the interior. It is also the cause of the illumination of every object in the interior, and determines the distribution of light incident upon it.

(iii) The luminance pattern determines the state of adaptation of the visual functions of users, and therefore their sensitivity; thus it determines apparent brightnesses corresponding to the luminance distribution.

(iv) If there is a visual task, the luminance pattern includes the luminance of the task and that of its surrounds, and therefore determines the adequacy with which it can be seen.

(v) The brightness pattern determines the comfort, or the glare or discomfort, experienced by users.

(vi) The brightness pattern determines the emphasis set upon certain features of the interior, or the lack of it, and is responsible for either concentration of attention, or distraction.

(vii) The brightness pattern is responsible for the revealing of the solid forms and the textures of architecture and objects, by modelling and shadows.

Workers in various countries have studied(2) certain features of these processes, in particular (i), (iv), (v) and to some extent (vi). Item (iii) has been much studied as a function of the visual process, but its consequences in illuminating engineering have been little appreciated. Little has been published about (vi) and (vii) except in an empirical and qualitative form which is not useful in design.

Each writer has naturally tended to concentrate upon the feature of interior lighting which is his special interest, and consequently the approach to the problem seems rather confused. Eventually designers will have to take all these features into account, balancing their various claims and combining them into a single harmonious and efficient design. They must therefore be armed with as many figures as possible, whereby they can express, predict and specify their intentions in terms which both the architect and the engineer can understand and handle. Figures must therefore be sought whereby recognisable degrees of luminosity, emphasis, modelling and discomfort may be expressed and specified so that, in the words of the Report, we can " measure, prescribe, predict and provide " them.

This paper is a contribution to three of the features of the design of the visual field which hitherto have not received much attention: Adaptation, Modelling and Emphasis. It makes an attempt at quantitative study of matters of formidable complexity, with the intention not merely of getting into the problems but of getting out again with a useful result. It does not claim to present complete solutions, nor to be more than a contribution to a much larger problem, and it should be read as an interim report of work still in progress. It has been necessary to compress much work and observation into small compass, and to give only outlines of experiments and summaries of results.

## (2) The Mechanism of Interior Lighting

An attempt has been made to portray the interrelation of the various factors, referred to above, in a diagram, Fig. 1. The three basic ingredients of lighting are (i) the light released in the interior, including its luminance, its spatial and its spectral distributions; (ii) the geometry of the whole interior, and (iii) the reflection properties of all the components of the interior. The light released, acting according to the geometry of the interior, causes *direct illumination* of all surfaces which it can reach. The flux involved in direct illumination is reflected from those surfaces according to their reflecting properties, and is *interreflected* in ways governed by the geometry and the reflecting properties; there results a *pattern of luminance and chromaticity* in the interior, which includes the light sources and all that can be seen.

It is convenient to consider the process in two stages. We therefore first derive

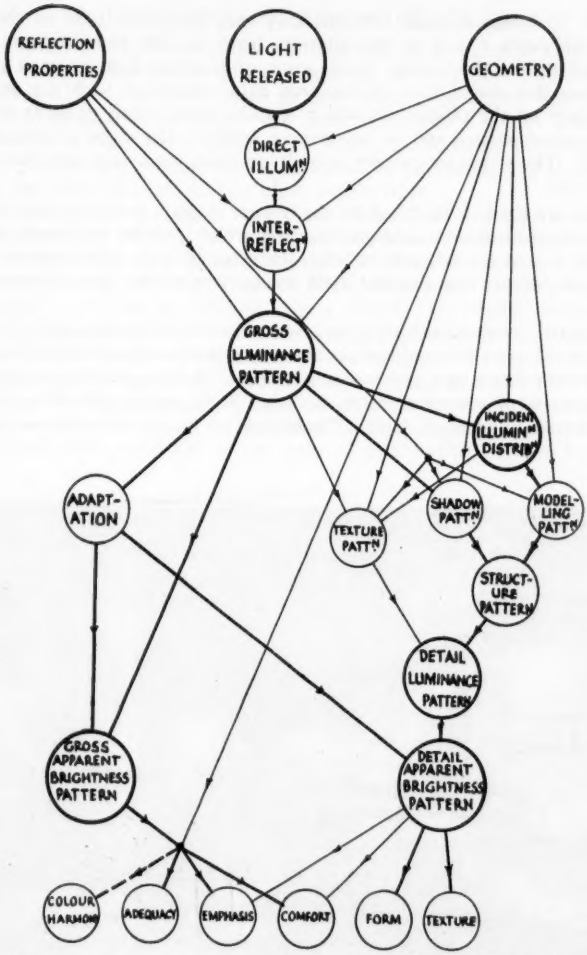



*Fig. 1. Mechanism of interior lighting. (For full titles, see text).*

from the interreflection process a *gross luminance and chromaticity pattern*, i.e., the mean brightness of fairly large parts of the field, not taking into account the smaller details, which are considered separately.

The gross luminance pattern provides the *adaptation levels;* and the observer, presented with the gross pattern while adapted to these levels, perceives *a gross pattern of apparent brightness and colour*—the general field of light, shade and colour as seen. From this pattern, sometimes together with other features of the geometry, arise final results such as *colour harmony, adequacy* of light for the task, if any, and *emphasis* and *comfort,* which may also depend upon features of the detailed pattern now to be discussed.

The formation of the luminance pattern of details may now be followed. The

gross pattern of luminance and chromaticity may be considered as the source of illumination of every object in the interior; from it, and from certain geometrical features, there results the *spatial distribution of incident light* at each point in the interior. From this distribution of incident light, combined with the geometry and reflection factors of the objects on which it falls, there result patterns of luminance called the *structure pattern* and *texture pattern* whereby the shape and finish of objects are displayed. The structure pattern is built up from modelling and shadow patterns as described later.

The structure pattern, modified by the texture pattern, forms what is here called a *detailed pattern of luminance and chromaticity* which may be extremely complex and subtle. From it, and the adaptation level, there results a *detailed pattern of apparent brightness and colour*—the detailed field as seen, whereby we recognise *form and texture*.

This diagram is necessarily simplified and is obviously inadequate and incomplete, particularly as it relates to simultaneous contrasts and to colour effects which are very complex and with which this paper does not deal. The diagram is presented only as a general scheme and is not relied on to be exact in all particulars: in some respects it anticipates explanations given later. Definitions of some of the terms are given in Appendix I.

*Fig. 2. Drawing office, by day.*

| Point | Luminance ft.-L | Apparent Brightness |
|---|---|---|
| 1 | 2430 | ? |
| 2 | 25·9 | 41 |
| 3 | 10·3 | 17 |
| 4 | 12·2 | 18 |
| 5 | 6·4 | 11 |
| 6 | 1700 | ? |
| 7 | 22·9 | 19 |
| 8 | 55·2 | 60 |
| 9 | 68 | 63 |
| 10 | 52 | 57 |
| 11 | 19·4 | 29 |
| 12 | 18 | 28 |
| 13 | 8 | 15 |

## (3) Adaptation and Apparent Brightness

The adaptation to brightness of the visual process is at once its most obvious and its most important feature to the lighting engineer, yet in practice little attention has been paid to it. We have approached lighting from photometry, and still think of the eye as "a very bad photometer," not recognising that it is not a photometer at all and responds to light quite differently from a photometer. Consequently there still exists in illuminating engineering a collection of anomalies and paradoxes which should long ago have been studied as clues to the truth.

For example, we have only a very crude sense of absolute level of luminance, and absolute levels are often at variance with experience. An amusing diversion at one annual dinner of this society, at which everyone present was asked to estimate the illumination, revealed great discrepancies in the estimates and the prize was won by a lady who chose a number at random. In a recent Test Match, when "bad light stopped play" the television operators reported a luminance of 120 ft.-lamberts; but in the splendidly-lit new Chamber of the House of Commons the illumination from the installation as actually used is in some places under 5 lm./ ft.$^2$ and the luminance is about 1 ft.-lambert (sloping roof). In the interior shown in Figs. 2 and 3 the ceiling, which appears far darker by day than by night, is actually 1½ times as bright. Daylight is customarily expressed as the ratio of illumination inside a building to the

*Fig. 3. Drawing office, by night.*

| Point | Luminance ft.-L | Apparent Brightness |
|---|---|---|
| 1 | 1·0 | 11 |
| 2 | 18 | 65 |
| 3 | 19 | 66 |
| 4 | 6·5-8·5 | 38-42 |
| 5 | 5 | 33 |
| 6 | 0·6 | 9 |
| 7 | 6·5 | 39 |
| 8 | 19 | 66 |
| 9 | 19·5 | 66 |
| 10 | 23 | 71 |
| 11 | 6·5 | 39 |
| 12 | 7·5 | 41 |
| 13 | 5·2 | 35 |
| 16 | 6·9 | 38 |

illumination outdoors, which was found to be a fairly stable index of users' experience, whereas absolute values of daylight are not; yet artificial light has always been expressed in absolute measure, which can be grossly misleading.

Paradoxes indicate a discrepancy between theory and practice, which means that theory needs an overhaul or an extension. There is in fact an approximate theory ready to hand and applicable to these problems, but it has not yet been applied. They seem unexpected only because it is so customary to think in terms of absolute levels and to regard them as figures of merit; such results should, however, be expected from knowledge of the functions of adaptation of the eye, and they can be explained and predicted by known data, at least approximately.

### (3.1) Apparent Brightness

In 1941 Hopkinson[3] with Stevens and the present author presented a series of curves relating the luminances in the visual field, the adaptation level of the eye and a scale of what was called "apparent brightness." These curves seemed to provide numbers which were in accord with experience and the present author has returned to them to express the experiences in various situations, with encouraging results. It is suggested that they should be applied to as many problems as possible and experience gained with them, to find whether they may not explain many existing anomalies and give a much more reliable approach to interior and exterior lighting.

In Fig. 4 the original data of Hopkinson have been replotted with logarithmic ordinates, which gives a more satisfactory shape for the curves, and a detailed interpolation has been made between the originals. This does not of course make the data more accurate but merely more convenient. Each curve gives the "apparent brightness" corresponding to various luminances in the field of view, and related to one state of adaptation. In an interior, if the luminance distribution is known, the adaptation level can be estimated for a particular direction of view and the appropriate curve may be chosen; using this, the luminance values can be translated into figures of "apparent brightness." These figures have been found to be a much better index of experience than the absolute figures. For example, in the interior shown in Figs. 2 and 3, the absolute values and the "apparent brightness" figures are shown for corresponding points. Though the absolute figures are quite anomalous, the apparent brightnesses of the ceiling are 41 and 65 for day and night conditions respectively, which accord quite well with experience.

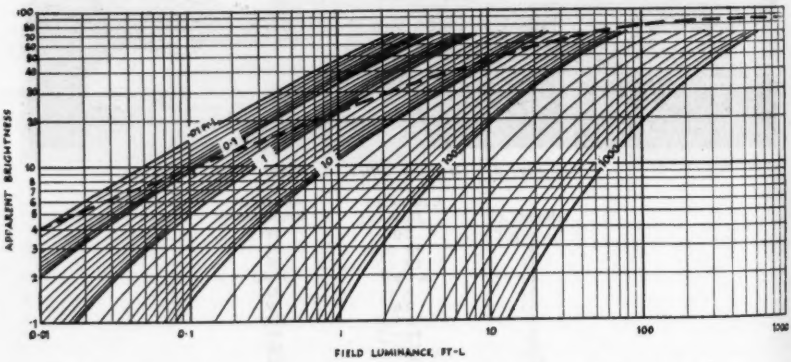



*Fig. 4. Curves showing Apparent Brightness as a function of Field Luminance and Adaptation Level (after Hopkinson).*

**(3.2) Adaptation Level**

There is evidence that as a user looks about in a room, or out of the window, his adaptation level changes continually and at a speed comparable with the time taken to fixate. There is therefore in a given situation not a single adaptation level, but many. It would be useful if the adaptation level were related to the mean luminance of the scene, and thus to the illumination at the plane of the viewer's eyes, but there is some evidence to suggest that the luminances which mainly determine the adaptation level are those near to the object of regard—very roughly within about 10 deg. of it.

The author has found figures of apparent brightness which agree better with experience if the adaptation level is estimated from luminance in this region than if it is taken from the illumination at the observer's eye, a procedure which overstresses peripheral elements in the field. It may be best to make a beginning using some such simple estimate and to gain experience, subsequently using a more accurate method when the laws governing adaptation are better understood.

**(3.3) Sense of Absolute Level**

On the diagram of Fig. 4 a dotted line is shown joining points for which the field luminance is equal to the adaptation level. It will be seen that for luminances up to about 30 ft-lamberts the curve rises slowly; thereafter it becomes nearly horizontal. This should imply a *limited* absolute sense of brightness, becoming less at high levels such as are found in daylight outdoors. If the apparent brightnesses are found for an interior for the luminances existing and for the case where all the luminances are reduced by a factor of one-half or one-third, it is found that the corresponding apparent brightnesses are reduced, but by a very much smaller factor. A typical set of figures is given in Table 1.

**Table 1**

| | Case 1 | Case 2 |
|---|---|---|
| Adaptation Level ... ... | 6 ft.-L. | 3 ft.-L. |
| Luminance Range ... ... | 4—8 ft.-L. | 2—4 ft.-L. |
| Apparent Brightness Range ... | 30—44 | 25—38 |

**(3.4) Scale of Apparent Brightness as Basis for Design**

Apparent brightness figures agree fairly well with experience of both interior and exterior scenes in daylight as the levels are reduced towards twilight, and the values found in different situations are reasonably consistent. There is not space to give details of all the experiments made so far, but it may be said that observation supports the notion of a genuine but restricted sense of absolute value which diminishes at higher levels.

There was also evidence that where there was a severe visual task (driving a car), *critical* visual performance was beginning to deteriorate when the apparent brightness fell to 40-50, though it was still quite easy to see and drivers had not switched on side lights; the light was still perfectly satisfactory for casual seeing. On reasonable assumptions it appears that the apparent brightness in the Test Match when "bad light stopped play" was of the order 50. From this and other evidence it seems possible to make a rough scale of interpretation of apparent brightness values, which has been done in Fig. 5. It is hoped that others will accumulate data and experience whereby these interpretations can be checked.

There is, however, evidence that a scale of apparent brightness may provide means for the architect to specify the result which he wishes to produce. Appendix III shows how such a specification can be easily transformed into one of luminance.

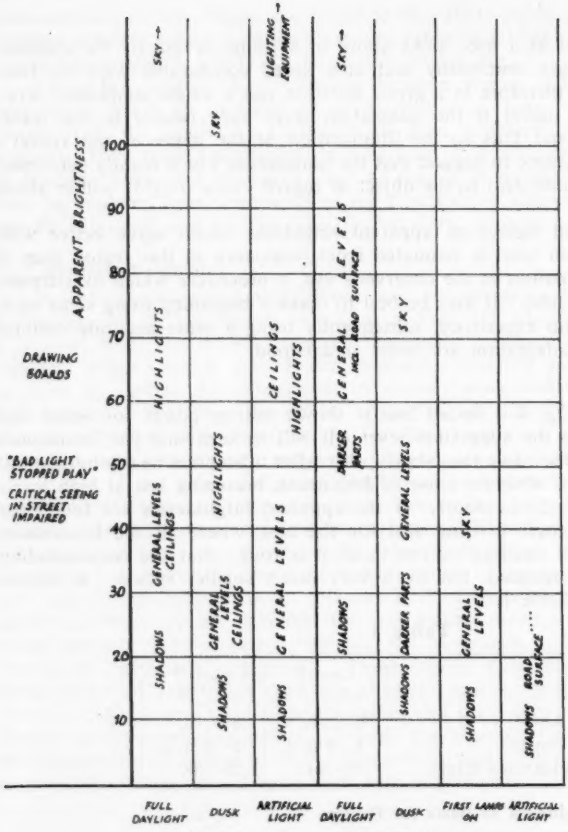



*Fig. 5. Scale of Apparent Brightness, with some typical levels.*

and then how the installation can be designed from that (or any other) specification of luminance distribution—in other words, how we may ascend from the bottom of Fig. 1 to the top, to derive the reflection factors, the light released in the interior and the geometry of the installation.

**(3.5) Daylight Factor and Apparent Brightness**

Consideration of adaptation explains the superiority of daylight factor over absolute levels as an index of the appearance of an interior as the daylight varies. Since daylight factor is a ratio based upon exterior illumination or sky luminance, it is tied to adaptation level in an interior. The daylight factor is nearly independent of exterior illumination, and apparent brightness varies only slowly with it; but absolute levels of luminance or illumination are approximately proportional to exterior illumination. Daylight factor, therefore, agrees more closely with apparent brightness than does illumination in varying daylight.

But since daylight factor relates to illumination, not luminance, it is not so reliable an index of the relative appearance of different rooms in which the reflection factors differ greatly.

## (4) The Revealing of Form and Texture

In a few branches of lighting the pleasing revealing of the forms of objects is consciously studied; examples are found in stage and studio lighting, shop-window lighting, and, to a limited extent, in shop interior lighting. In most other interior lighting schemes the subject is ignored. The appearance of the interior by night is often quite different from its appearance by day; there are examples of interiors which by day are masterpieces, but which by night are unrecognisable and quite spoiled. By day, light enters most buildings from large side windows and a more or less coherent flow of light takes place across the interior, causing a regular structure pattern whereby the solid forms of architectural features and furniture, and of people in the room, are coherently revealed. When such a room is lighted by the conventional regular array of lighting equipment symmetrically arranged throughout the room, there is no coherent flow of light; architectural features are shown by an inconsistent modelling pattern and a muddle of shadows from light sources in many directions, so that the form may be concealed or even a misleading form appears (4). In many such interiors there is no relief; the user moves about vainly looking for some difference in the lighting for a change.

This section of the paper attempts to measure and define quantities relating to the modelling effect, and studies in existing interiors of the modelling and appearance which occurs by day and by night.

### (4.1) The Mechanism of the Revealing of Form

#### (4.1.1) *Modelling Pattern*

Light reaches any point in an interior from all directions from the surrounding luminance field, and in differing amounts in each direction: there is thus a spatial distribution of incident light, in consequence of which a small surface at the point, turned about into different orientations, will receive differing illuminations and will take up differing luminances. A solid object, considered as built up from a number of such elements, will in general present a "modelling pattern" of luminance which, if it is matt, results from its geometrical shape and from the distribution of incident light.

A given distribution of incident light clearly has capabilities for revealing form, or "modelling," which it should be possible to measure and express. A beam of nearly parallel light in a room with black walls clearly has the greatest possible capabilities for modelling; in such a beam the illumination of a surface element will vary as the cosine of the angle of incidence. At the other extreme is a snowfield with snow falling in thick overcast, when the modelling capability is zero. One obvious measure of the modelling capability is the rate of change of illumination of a small surface element as a function of orientation; this might well form the basis of a formal definition, but a more convenient measure is discussed in Section 4.3.2. The computation of modelling properties in any but the simplest conditions is likely to be very involved,* and it is more important to devise means for studying these effects experimentally in practice and for finding a simple index of their amount.

The modelling capabilities of light at a point can be explored by placing a small standard structure there, the appearance of which can be studied. The most satisfactory so far found has been a small white polyhedron as shown in Fig. 6, having 26 sides, inclined to one another mostly at 45 deg.† The change in luminance between one facet and its neighbours on such a solid is a rough measure of the rate of change of illumination with respect to orientation. This solid gives a clear picture of the

* Since this paper was written, simple approximate methods of calculation of these properties have been devised.

† The true angle between adjacent facets in the rings which are inclined at 45 deg. to the vertical is 31.2 deg.; at all other edges the true angle is 45 deg.

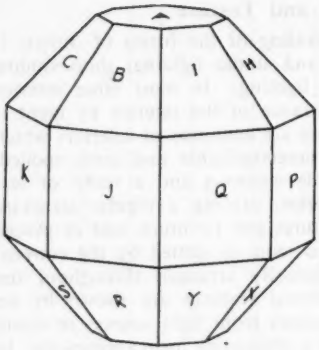
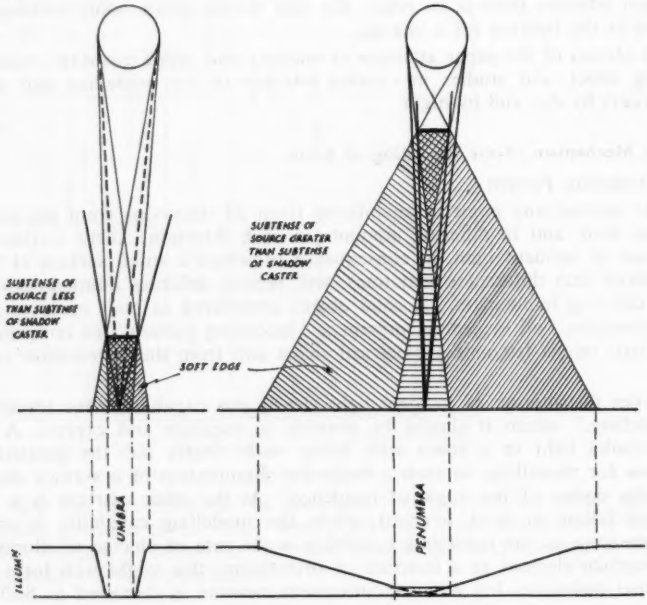



*Fig. 6 (left). Standard polyhedron for study of modelling showing numeration scheme.*

*Fig. 7 (below). Formation of shadow.*




kind of modelling, and one which can be easily recorded photographically and which lends itself to description and to further experiment. Apparatus based upon this object is described in Section 4.2.1.

(4.1.2) *Shadow Pattern*

Shadow and modelling are so closely allied that they are often thought of together, but they are clearly separable and must be distinguished. *Modelling* occurs with objects which are not plane, in illumination which is directional, when the illumination of one part of the object differs from that of another because its orientation with respect to the directional lighting is different. *Cast shadow* occurs when the illumination of some surface is reduced because some projecting object,

or part of an object, is interposed between the surface and the source of its illumination. Modelling effects can occur without cast shadow, for example with the "Standard Structure" polyhedron just described, and strong cast shadow can occur with very little true modelling.

Shadows have been extensively studied by Norden(5), who has suggested various numerical means of expressing them. In the present work these have not yet been followed up, but shadows have been recorded and studied qualitatively. Shadows may be dense with sharp edges, or so soft as to be imperceptible; the difference depends upon the relative angular subtenses of the source of light and of the shadow-caster, measured at a point on the illuminated surface, and upon the contribution which that source makes to the total illumination. The density also depends upon the reflection properties of the illuminated surface. If the source subtends a small angle and the shadow-caster a larger one (Fig. 7), the shadow will have a fairly sharp edge and the light from the source will be cut off entirely, i.e., an umbra will be formed: if that source supplies most of the illumination, the shadow will be dense. The width of the soft edge to the shadow is the projection of the source on to the shadowed surface through a point on the edge of the shadow-caster in an appropriate plane. If the subtense of the shadow-caster is less than the subtense of the source, then the light from the source will not be wholly cut off and a penumbra is formed; the presence of a penumbra usually implies a soft edge to the shadow. If several sources of small subtense contribute to the illumination at a point, multiple shadows will be formed having sharp edges, but they will be weak because each shadow is lighted by all the other sources.

Although cast shadow can exist with little modelling and modelling without cast shadow, nearly always in practice they occur together as the result of a common cause —directional lighting. If more light is incident from near a given direction than from other directions, then surfaces facing that direction will receive most illumination and surfaces screened from that direction will have shadow cast upon them. There is a difference of mechanism, however, which may be important. Modelling is related to the spatial distribution of illuminaton at a point and is not dependent upon the cause of the illumination. Cast shadow is related to the surrounding luminance field that can be seen from that point, not to the spatial distribution of illumination at the point. The modelling effect at a point is almost independent of the subtense of the source, up to sources subtending about one steradian—i.e., a large, diffuse source has almost the same modelling effect as a small point source (see Section 7.3). The shadow-casting propensities of two such sources are, however, quite different; the first will produce soft, diffuse shadows often with only penumbra, which can scarcely be perceived, whereas the second will produce dense shadows with hard edges which are very obvious.

Since modelling and shadow casting usually have a common cause, they operate together in the revealing of solid form, and together produce the "Structure Pattern." By the behaviour of the two phenomena we deduce both the shapes of objects and the character of the lighting. For example, in very diffuse lighting there is little modelling and shadows are very soft; form is not well revealed. Strong modelling but soft shadows occur, for example, in a room with a large window at one side. Strong modelling with hard-edged shadows occur in sunlight; the shadows are denser as the sky is darker and the sun brighter. Extremely hard modelling and shadows occur on objects lit by a single source in dark surroundings.

The shadow-casting propensities of light at a point may be studied by using a small standard shadow-caster. Norden has used many forms; an apparatus in which a convenient form is used in association with the polyhedron structure for modelling is described in Section 4.2.1.

(4.1.3) *Texture Pattern*

Most common objects have reflection properties which are neither matt nor specular; they are usually either combinations of the two acting simultaneously (mixed reflection) such as, for example, glazed china, or properties which are neither specular nor matt but preferential, for example, slightly diffusing aluminium. The brightness distribution of a matt surface depends only on its illumination; of a specular surface only on the surrounding luminance field. The brightness distribution of a preferentially reflecting surface depends usually upon both the illumination distribution and on the surrounding luminance field.

Such surface properties modify the structure pattern to produce "texture pattern." The modification depends on the geometry of the surface, the reflection properties and both the spatial distribution of illumination at the object and the luminance field which the object can see. In Fig. 8 are shown objects which exhibit structure pattern, shadow pattern and texture pattern which can be distinguished.

**(4.2) The Study and Measurement of Modelling and Shadow**

Apparatus has been devised for the study of the modelling and shadow in interiors, and the measurement of incident illumination distribution. Conditions have to be

*Fig. 8. Group of objects showing modelling patterns, texture patterns and shadow patterns.*

studied both at the walls, where they are responsible for the revealing of architecture, and in space within the interior where they affect the appearance of people and furniture.

(4.2.1) *Polyhedron and Shadow Apparatus*

Apparatus was constructed for recording the conditions at a point by photography with a miniature camera; the final form is shown in Fig. 9. To record modelling properties of the light, the polyhedron shown in Fig. 6 is mounted in a frame supported on an upright on a wheeled base at a height of about 4 ft. 6 in. from the floor. A camera is supported on a bracket on the lower part of the upright to photograph the polyhedron directly from below and, with the aid of three mirrors, from two sides and from above; the four views cover all the facets, most of them twice. Beside the polyhedron and on the same horizontal plane is the shadow-caster apparatus. This consists of a horizontal 7-in. disc of flashed opal glass, ground matt on the opal side which is uppermost. At the centre of the disc is a small upright black post.

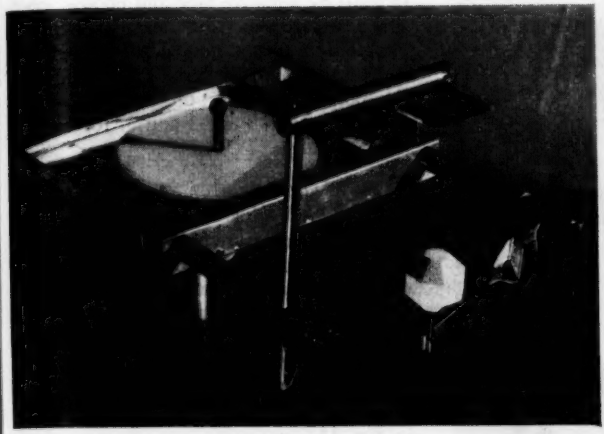
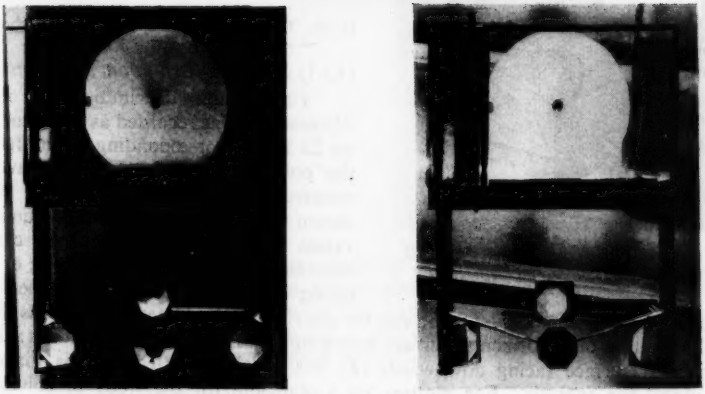


*Fig. 9. Polyhedron and shadow apparatus for study of modelling and shadow.*



(a) (b)

*Fig. 10 (a) and (b). Photographs from polyhedron and shadow apparatus,*
*(a) Corresponding to Figs. 12 (a) and 13 (a) showing azimuth modelling, by day.*
*(b) Corresponding to Figs. 12 (b) and 13 (b) showing altitude modelling, by night. Taken at Point marked F, Figs. 2 and 3*

$\frac{1}{4}$-in. diameter and $1\frac{1}{2}$-in. high with a ball top $\frac{5}{8}$-in. diameter. This is the shadow-caster, and the camera, viewing the lower side of the disc, records the pattern and strength of shadows on it. The layout is not perfect—for example, it will not show shadows from light directed nearly horizontally—but it has proved fairly satisfactory in practice. Since it is often necessary to turn the apparatus to avoid a shadow or obstruction, to record the orientation an arrowhead is marked on the disc of the shadow-caster which is turned to the principal axis of the room. A data-tablet identifies the photograph. There is also an arrangement for photographing a step wedge, but this has not been much used. Two typical records appear in Fig. 10.

(4.2.2) *Wall Polyhedra*

For recording the lighting conditions on a wall, several larger half-polyhedra were constructed of cartridge paper stuck on to sheets of white card; they can be attached

*Fig. 11. Apparatus for measurement of spatial distribution of incident light.*

to walls by adhesive tape and photographed. The base card was made fairly large, and the photograph gives a good idea of shadow as well as of modelling, since the shadow of the polyhedron falls on the card. Some may be seen in Figs. 2 and 3, for example near point 8.

(4.2.3) *Measurement of Spatial Distribution of Incident Light*

For the measurement of the spatial distribution of incident illumination, a holder was made for supporting a photocell at orientations corresponding to those of the facets of the polyhedron. The apparatus was mounted on a camera tripod at about the same height as the polyhedron apparatus for which it is substituted. It is illustrated in Fig. 11.

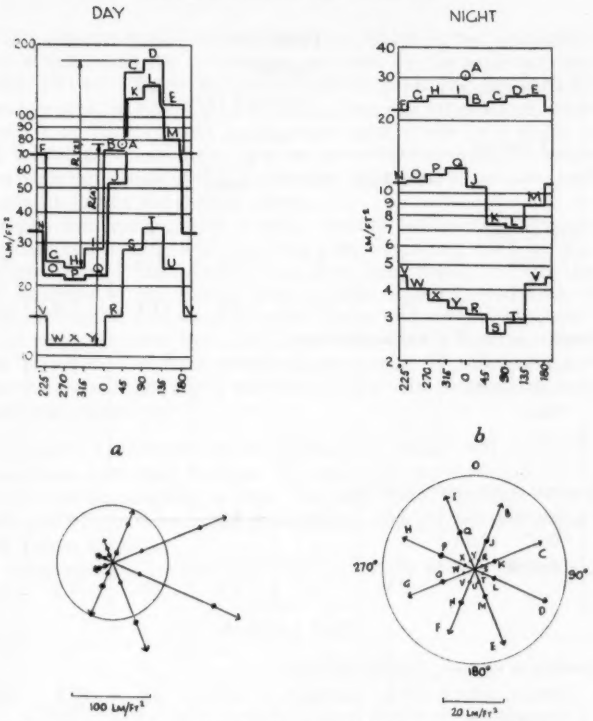
**(4.3) The Portrayal of Spatial Distribution of Incident Light**

(4.3.1) *Spatial Distribution Diagrams*

The spatial distribution of incident illumination was recorded as the illumination on 26 facets corresponding to the facets of the polyhedron. Two schemes have been adopted for portraying the results. One is shown in Fig, 12, where the illumination values are plotted on logarithmic cartesian co-ordinates, one series of the ring of facets facing 45 deg. upwards (B—I) (See Fig. 6), one for the vertical facets (J—Q) and one for the ring facing 45 deg. downwards (R—Y). The illumination on a horizontal surface facing upwards (A) is shown by a dot: that on a horizontal surface facing downwards (Z) was usually omitted. This diagram is more useful for analysis. For plotting on a plan and for the study of coherence a simpler polar diagram was used with vectors indicating the horizontal directions, each carrying three arrowheads of different type representing the illuminations on planes 45 deg. up, vertical and 45 deg. down respectively. The illumination on a horizontal surface was represented by a circle whose radius corresponds to the value. Linear scales were used. Typical polar diagrams are shown in Fig. 13.

(4.3.2) *Modelling Index*

For expressing the modelling capacity of lighting by a single number, after some experiment it appeared that a good index, more convenient and sensitive than the rate of change of illumination with orientation, was the "consistent range," i.e., the greatest range of illumination in each row of facets over which the illumination continuously increased or decreased, expressed as a ratio (see Fig. 12). This gave numbers which distinguished most consistently between various distributions put in order of increasing modelling effect by judging the photographs of the polyhedron. It is also easy to ascertain. The modelling indices used were generally the consistent ranges for the upper, middle and bottom rows of facets on the polyhedron, the mean for the three and the maximum in any vertical plane.




*Figs. 12 and 13. Portrayal of spatial distribution of incident light by Cartesian and Polar Coordinates (a) by day, showing marked azimuth modelling; (b) by night, showing marked altitude modelling. For interior shown in Figs. 2 and 3, see Figs. 10 (a) and 10 (b).*

*R(z) - Consistent Range in Azimuth for upper Row.*
*R(a) - Consistent Range in Altitude.*

(4.3.3) *Azimuth and Altitude Modelling*

It is convenient to distinguish two characteristic forms of modelling which are met in practice. In one typical form, the illumination is nearly uniform in all azimuths but changes markedly as the normal to the facet moves in vertical planes: maximum illumination usually occurs on a horizontal surface. This is referred to as "altitude modelling." In another typical form, illumination changes markedly as the normal to the facet rotates in azimuth; there is usually less change as it rotates in vertical planes. Maximum illumination usually occurs on a surface either vertical or inclined upwards at 45 deg. This is referred to as "azimuth modelling." The mean azimuth consistent range is the most useful single number for a modelling index. The two types are illustrated in the photograph of Fig. 10 and the corresponding plots of Figs. 12 and 13 (a) and (b).

**(4.4) Some Typical Results**

(4.4.1) *Summary of Modelling Results*

Surveys have been made in a number of interiors by day and by night, the systems of daylight and of artificial light being different. Tables 2 and 3 give the modelling indices (consistent ranges) found. The same interiors occur for both conditions.

**Table 2**
**Daylight**

| Ref. | Location | Modelling Indices | | | | | Notes |
|---|---|---|---|---|---|---|---|
| | | Azimuth | | | | Altitude | |
| | | 45 deg. up | Vert. | 45 deg. down | Mean | | |
| *Single side window (bay)* | | | | | | | |
| 166–170 | Lounge | 4.2 | 7.5 | 5.2 | 5.6 | 3.8 | Mean of 4, near walls. |
| | | 18 | 28 | 8.3 | 17.1 | 5.8 | In bay |
| *Multiple Windows in two Walls at Right Angles* | | | | | | | |
| 206/I | Library, med. oak panelling | 14.0 | 14.8 | 10.5 | 13.1 | 7.1 | Mean of 3. Modelling judged excessive by some |
| *Multiple Windows in two Opposite Walls* | | | | | | | |
| 207/F, G/I | Drawing Office, light decoration | 7.0 | 6.6 | 3.5 | 5.6 | 6.9 | Mean of 2, near windows |
| 207/H/I | | 2.1 | 2.6 | 2.3 | 2.3 | 4.4 | On centre-line between windows |
| *Multiple Windows in all walls, mainly clerestory* | | | | | | | |
| 208/I | Church, light decorations | 2.2 | 2.8 | 2.3 | 2.4 | 10.5 | Mean of 3 |
| *North Light* | | | | | | | |
| 160 | Laboratory, mainly light decorations | 5.7 | 14 | 5.0 | 8.2 | 14 | 1 position |
| *Outdoors, Open Situations* | | | | | | | |
| 171 | Full sun, 57 deg. el. | 12 | 6.3 | 3.1 | 7.1 | 10 | Approx. |
| 173 | Weak sun, 47 deg. el. | 6.5 | 5.3 | 1.5 | 4.4 | 13 | |
| 172 | Overcast | 1.7 | 1.6 | 1.2 | 1.5 | 7.7 | Heavy irregular cloud |

A single number cannot convey the differences of the distributions involved, which there is not space to reproduce. An interesting feature is the noticeable effect of decorations; for example, a large dark door, or one dark region, will considerably reduce the illumination on the vertical facet facing it; an aisle between desks or pews has a similar effect usually on the facets facing 45 deg. downwards. Some of the results quoted above are affected by such effects. Light decorations reduce modelling and dark decorations increase it.

(4.4.2) *Effects of Single and Multiple Sources*

Several experiments have demonstrated the marked reduction in modelling effect which occurs when the incident light arrives from more than one principal direction

The most striking instance was in an amateur stage lighted by two spotlights only, about 90 deg. apart, which made the polyhedron, as seen by the audience, appear almost uniformly bright all over. There was thus almost no modelling, but hard shadows were formed. This is a striking example of an effect found in installations, which is noticeable in the results of Tables 2 and 3. A single light source or a single side window gives marked modelling in azimuth: two or more light sources or windows lighting from different directions and giving comparable illumination usually result in much less modelling, each killing the other's effects.

For example, the lounge, with a single central fitting, shows reasonably large azimuth modelling comparable with that from the single bay window, but with much more altitude modelling. The addition of a local light greatly reduces the modelling. The multiple windows of the library gave a large azimuth modelling effect, partly because windows were in two walls at right angles and certain windows were partly obstructed, and partly because the decorations were dark. The day modelling effects in the church, however, with many windows were much like those for artificial light, for the windows were set high above the test locations and were placed rather similarly to multiple artificial lights.

(4.4.3) *Characteristic Differences of Modelling in Daylight and Artificial Light*

A characteristic difference between the modelling by day and by night usually occurs, of which the distributions in Figs. 12a and 12b are typical. The distributions shown refer to the interior seen in the photographs of Figs. 2 and 3, the drawing office (Ref. 207) of Tables 2 and 3.

In most installations of artificial light there is usually strong altitude modelling; the

**Table 3**
**Artificial Light**

| Ref. | Location | Modelling Indices | | | | | Notes |
|---|---|---|---|---|---|---|---|
| | | Azimuth | | | | Altitude | |
| | | 45 deg.up | Vert. | 45 deg. down | Mean | | |
| *Single Central Fitting* | | | | | | | |
| 164 | Lounge | 6.4 | 6.6 | 1.7 | 4.9 | 15 | 1 position |
| *Single Central Fitting plus Local Light* | | | | | | | |
| 163a | Lounge | 3.3 | 5.2 | 1.5 | 3.4 | 10.9 | Mean of 2. Results sensitive to position |
| *Multiple Suspended Fittings—RLM type Reflectors* | | | | | | | |
| 161, 162a | Laboratory | 1.2 | 2.2 | 2.0 | 1.8 | 15.5 | Mean of 2. Some variation due to decorations |
| *Semi-Indirect Type* | | | | | | | |
| 206/II | Library | 1.3 | 2.0 | 1.6 | 1.6 | 10.5 | Mean of 3. |
| *Diffusing Type* | | | | | | | |
| 208/II | Church | 1.5 | 2.7 | 1.4 | 1.9 | 10.2 | Mean of 2. |
| *Louvred Ceiling* | | | | | | | |
| 207/II | Drawing Office | 1.2 | 1.5 | 1.6 | 1.4 | 12.3 | Mean of 3. |

greatest illumination occurs on horizontal surfaces (Fig. 12b). In installations having more than one light source the illumination at various azimuths is nearly constant, though it may be affected by the presence of adjacent decorations. By day, with either side windows or a north-light roof, the distribution of Fig. 12a is typical. Here the maximum occurs either on a vertical surface or one inclined at 45 deg. upwards (of the surfaces measured) and the illumination on horizontal surfaces is less, showing strong "azimuth modelling." The altitude modelling is usually medium or strong, but less than the azimuth modelling.

In a small room lighted by a single central light source, the modelling distributions are very much the same by day and by night—the latter showing strong azimuth modelling—except that the direction of greatest illumination by day is towards the window, so that the directional effect is more or less parallel throughout the room, whereas at night it centres on the lighting fitting. But the lighting cannot be said to be incoherent by night, as it is in an interior with multiple lighting fittings.

(4.4.4) *Modelling in Exterior Daylight*

Typical distributions obtained on open sites outdoors show in overcast conditions strong altitude modelling and little azimuth modelling, and in sunny conditions strong azimuth modelling and much less altitude modelling. There is an interesting similarity between the modelling in the sunshine outdoors and that in a side-lit room by day indoors, and between overcast weather outdoors and artificial light indoors.

(4.4.5.) *Preferred Modelling*

From observation it appears that most people prefer modelling with a fairly strong azimuth component, and that they regard altitude modelling without azimuth modelling to be flat and dull. The connection with the modelling occurring outdoors, just referred to, is surely significant. In fact, many people seem to confine their conception of modelling to modelling in azimuth, which they sometimes call "dramatic," and it is significant that lighting for the stage and studio uses a large proportion of light from the side.

There is probably a dynamic effect as well as a static effect in modelling. When there is well-marked azimuth modelling people make use of it, moving to "catch the light," putting ornaments or flowers advantageously and enjoying the variations which such a distribution affords. Weston has suggested that the variation of daylight with time is attractive and might be copied; a possible alternative may be the provision of sufficient azimuth modelling for people by changing their position to enjoy a spatial variation of both amount and distribution of light. Where there is only altitude modelling and little azimuth modelling, the spatial distribution does not change much in different positions and change of position affords no relief.

(4.4.6) *Direction of Modelling and Observation*

For an appearance of solidity to be obtained, it is necessary for the directions of illumination and view to be well separated so that the modelling and cast shadow can be seen. A separation of about 60 deg. often gives an optimum effect. Objects seen down light have an objectionably flat appearance, like that of a flashlight photograph, the brightest surfaces being those facing the observer. Moreover, wherever directional lighting exists there must be some directions of view in which objects will be seen "up light" with their visible face in shadow. This might be thought to be a grave disadvantage, yet in an interior with North-lights in which users may have to work in any direction, the effect, which was present, was not noticed and users prefer daylight to artificial light, even though there is no benefit of view outside.

(4.4.7) *Necessary Amount of Modelling*

To obtain an idea of the amount of modelling light which is desirable for various describable degrees of modelling, a direct experiment was made. A sitter was

viewed in a room lit by four diffusing fittings, so located that the spatial distribution of illumination upon the sitter was as nearly uniform as it was likely to be in an interior without taking special precautions. A reflector lamp was arranged to light the sitter's face from an angle of about 25 deg. above the horizontal, and at 0 deg., 30 deg., 60 deg., 90 deg. and 120 deg. from the direction of view. A panel of observers was asked to set the amount of light from the spotlight so that the directional effect was (i) just perceptible, (ii) adequate and (iii) strong at each of these angles. The mean settings were found for each angle and criterion, and for each criterion and angle the spatial distribution of incident light at those settings was recorded, and photographs were taken of the sitter and of the polyhedron apparatus at the same location.

Fig. 14 shows some of the results, giving the sitter (a) with the spotlight off, and (b), (c) and (d) with the spotlight at 30 deg. from the line of sight and set at the mean settings for just perceptible, adequate and strong modelling respectively.

Fig. 15 shows the photometric results, in which the consistent ranges are plotted, for the means of the upper, middle and bottom rows of facets on the polyhedron as a function of the angle between the directions of view and of illumination. The results are interesting in that the modelling index does not vary very much between 0 deg. and 60 deg., after which it rises somewhat to 90 deg., with a tendency to fall again at 120 deg. For just perceptible modelling the value is 1.5 to 2. For adequate modelling it is 2½ to 5 and for strong modelling 4½ to 10. These values compare with those found in interiors (Tables 2 and 3) where values of 4 or 5 up to 15 or 17 (near windows) have been found in side-lit rooms by day, and values of 1½ to 2½ have been found by night in interiors with multiple sources. An interior (Ref. 206, Table 1) in which the consistent azimuth range by day was 12-13 was judged by some observers to have too much modelling.

## (5) Emphasis

Lighting for emphasis is lighting a scene in such a way that the attention of users of the interior is drawn to certain of its features. It is a well known device in stage lighting, and the phrase "in the limelight" testifies to both its age and its importance. It occurs naturally, and architects use it consciously, in daylight in many interiors.

Emphasis can be brought about by merely increasing the luminances of the region to be emphasised; it may also be due to increased modelling or to contrast, or to a difference in hue or saturation of colour. For example, in the church of Fig. 16 the Sanctuary and Altar have been emphasised by increasing their brightness by floodlights, some at the back of the screen and some directed at the Altar from both sides, by which the brightness of these features has been increased considerably. The luminances and apparent brightnesses are indicated. In Fig. 17, half the screen floodlights have been extinguished and half the Altar floodlights on one side. The result is that the luminance of the Altar and its apparent brightness have been reduced, but the modelling considerably increased; in the opinion of most observers the emphasis of the Altar has been considerably enhanced by the increased and more coherent modelling despite the reduction in brightness.

Emphasis can be achieved by contrast of an object with its background. An object may be comparatively inconspicuous and be little emphasised when seen against a light background; by merely reducing the reflection factor of the background, without altering the lighting of the object, it may be made much more conspicuous.

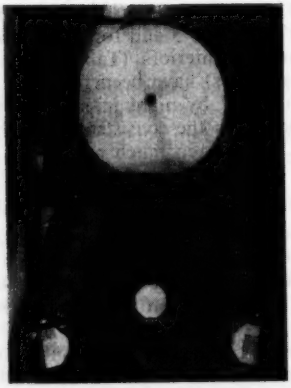
When emphasis is due solely to increased brightness, it may reside in the brightness of the highlights which become brighter than would be expected for the situation. The amount of light necessary to achieve emphasis will depend upon the reflection factor and upon the size of the feature to be emphasised. There is some evidence

(a)

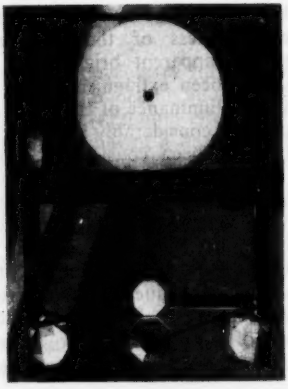
*Fig. 14 (a)-(d). Sitter with directional lighting at 30 deg. from direction of view.*

*(a) None*
*(b) Judged as 'Just Perceptible.'*
*(c) Judged as 'Adequate.'*
*(d) Judged as 'Strong.' (See facing page).*

(b)



(c)



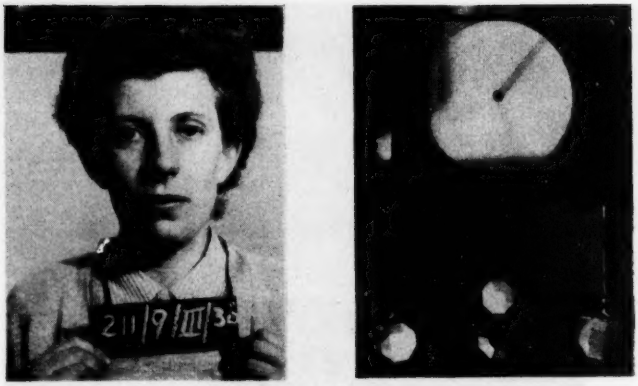


*Fig. 14 (d).*

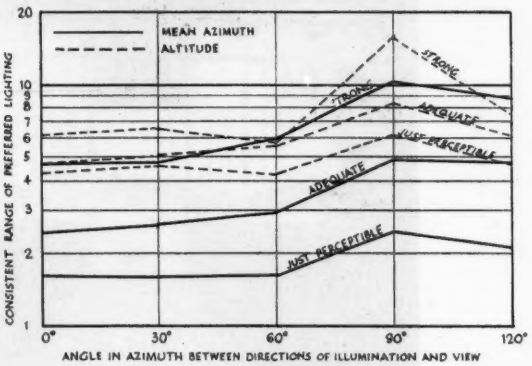



*Fig. 15. Curves showing consistent ranges of preferred modelling for conditions of Fig. 14.*

that an added illumination of about three times the general illumination is the least that is likely to succeed.

Since emphasis can be achieved in several ways, and since any attempt to achieve it will probably bring about more than one effect at the same time, its experimental study and quantitative expression is less easy than that of modelling. Some results have been obtained and work is in hand, but there is little point in making measurements unless the quantity to be measured can be isolated. There is more to be learned from qualitative study and the opinions of a judging panel and several interiors have been so studied systematically.

## (6) Some Effects in Complete Interiors

Many of the effects observed in complete interiors have already been reported; some general observations are given here.

The difference between the appearance by day and by night is not wholly due to light distribution. The effect of view is most important and cannot be well conveyed by photographs. By day a room seems a pleasant shelter from the weather from which one looks out to the outside world; the outside view is usually the natural centre of attention. Ceilings are usually fairly dark and unobtrusive, and rooms look lower. By night the windows become deadlights and in themselves are blank and dull, giving a "shut-in" effect; ceilings are generally bright and rooms look smaller

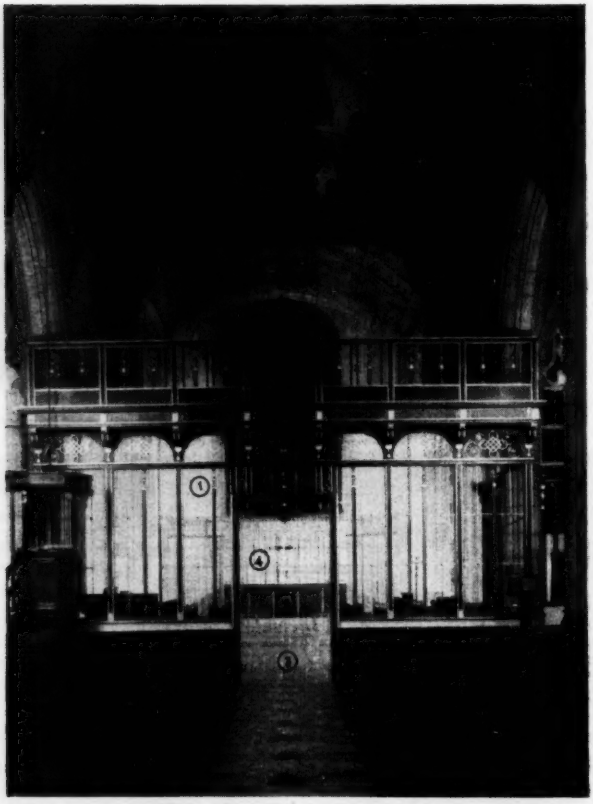



*Fig. 16. Church, with Sanctuary and Altar lighted symmetrically.*

| Point | Luminance ft.-L | Apparent Brightness |
|---|---|---|
| 1 | 1·4 | 29 |
| 2 | 0·27 | 11 |
| 3 | 0·5 | 16 |
| 4 | 1·1 | 24 |
| 5 | 0·21 | 9·5 |
| 6 | 0·11 | 6·2 |
| 7 | 0·057 | 4 |

and higher. A natural centre of attention may have to be found within the room itself, and if there is not one the effect may be one of aimlessness.

A lighting fitting in the centre of a room gives a very flat and dull effect, the cause of which is not obvious. There is usually good modelling of objects in the room, but all four walls are about equally lighted so that there is no particular emphasis, and in a small room the line of sight is usually not far from the direction of maximum illumination so that the modelling and shadows are not well seen. The dull effect is probably due mainly to absence of emphasis, and partly to modelling which cannot easily be seen. A similar effect occurs on ceiling panels in multiple-fitting installations when fittings are placed in the centres of the panels.

The side lighting in daylight of most rooms, and the top lighting by night, has an effect which is sometimes discernible, that the pattern of luminance in the room depends

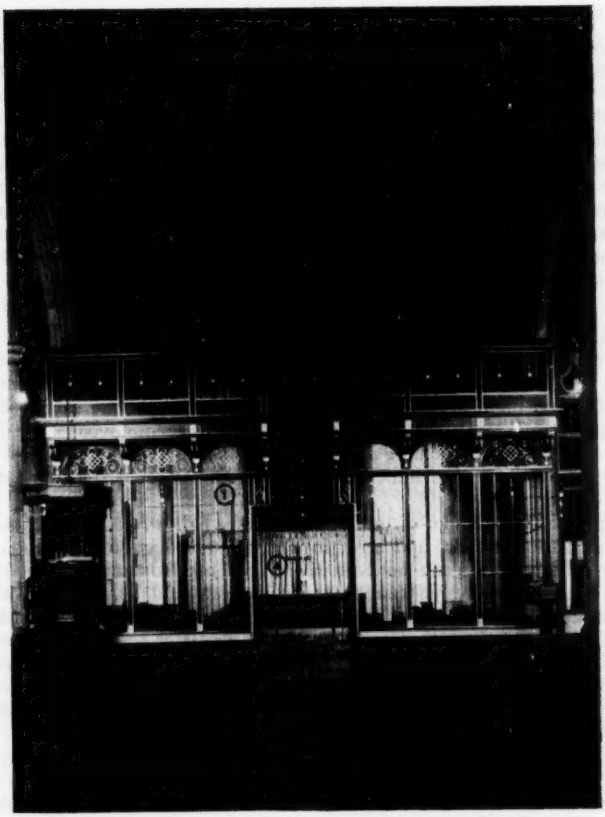


*Fig. 17. Church, with Sanctuary and Altar lighted from South Side only.*

| Point | Luminance ft.-L | Apparent Brightness |
|---|---|---|
| 1 | 0·6 | 21·5 |
| 2 | 0·19 | 11 |
| 3 | 0·45 | 19 |
| 4 | 0·43 | 18 |
| 5 | 0·17 | 10 |
| 6 | 0·11 | 7·8 |
| 7 | 0·057 | 5·3 |

more upon form and texture by day and more upon reflection factor by night. There is a disadvantage here in the provision everywhere of light decorations, since at night there is little with which to form an interesting pattern of brightness.

The greater coherence of directional effects in daylight was very noticeable, showing itself mainly in the more consistent appearance of architectural features. The effect was not confined to rooms lit from one side; it is due largely to the positions of the windows at the walls, compared with lighting fittings hung in mid-air. Light from windows usually strikes some walls and the ceiling obliquely; light from fittings hung in mid-air strikes walls more nearly normally and usually from several incoherent directions.

## (7) Possible Effects Upon Lighting Practice

Hitherto lighting practice has been traditionally based upon the provision of uniform illumination on a working plane, and very often it still is in spite of interest in "Brightness Engineering." It is restricted, mainly in the interests of comfort, by limits placed upon certain factors to avoid discomfort glare, high brightness ratios, etc. With this in mind there has been a move to high reflection factors and matt surfaces, but the result of following these instructions not too intelligently has often been a light-painted interior drenched with light from all directions, with very high and uniform luminance, with little modelling, emphasis or relief. However, many more modern interiors show another approach, in which the lighting is an integral part of the interior design; importance is given to emphasis and to recognising that if anything is to be emphasised, certain other features must be subdued.

### (7.1) Design Procedure

The designer's first problem is to decide what he wants to do: what impression of light he desires: where the emphasis should be, and how much: what degree of modelling is required and from what directions: what the colour effects shall be and approximately what pigments (and reflection factors) and lights he shall use to achieve them: and in general terms the system of lighting to be employed. The lighting design can be laid down by deciding first, with the help of Fig. 5, the gross pattern of apparent brightness. Then as indicated in Appendix III the gross luminance pattern can be derived using Fig. 4.

The Report on the Design of the Visual Field[2] indicates a possible but laborious method of calculation by trial and error involving interreflection calculations, but by a fortunate circumstance this can be avoided by working from the specified luminance distribution; the lighting design can be found directly and very simply, avoiding all complex interreflection theory and arriving at the illumination to be provided on each surface directly from the lighting equipment. Thereafter the problem becomes one of simple illuminating engineering. This method of calculation is indicated in Appendix III and may be of some importance. It should be possible to extend it to the calculation of the pigment colours necessary to achieve a specified colour appearance.

The type and position of the lighting equipment which provides this direct lighting will have to be decided from considerations of modelling. The amount of modelling received from illumination from other surfaces can be estimated by methods analogous to those for designing the gross brightness pattern; the lighting equipment must be so located that the direct light from it will arrive from such directions as to achieve the desired degree and direction of modelling for the various surfaces. Naturally this aspect of design will depend mainly upon experience and is less simple to calculate.

### (7.2) Lighting Equipment

There is often little need for a regular array of lighting equipment hung throughout the interior, unless the architect needs it for reasons of appearance. The desired effects may be best achieved by equipment concealed near the walls. Alternatively, modelling and emphasis may have to be achieved by supplementary lighting superimposed on a general scheme, perhaps from reflector lamps in concealed positions if the interior is suitable. In some interiors there may be lighting fittings whose main function is decorative and which may be arranged symmetrically, while the real lighting of people and of walls may be done by concealed lights.

There is the possibility of producing modelling effects by the use of lighting equipment in conventional positions but with an asymmetrical light distribution. This may succeed to a limited extent in the modelling of people and furniture, but it seems unlikely that it can succeed in the directional lighting of the enclosing surfaces which must depend on the positions of the lighting units.

**(7·3) Modelling and Glare**

Azimuth modelling cannot be achieved without more light being provided from one side than from another, and in most interiors users may look towards the source of this greater illumination. There is thus an inherent tendency to glare but it can be avoided by two methods—by using a bright source of small subtense, so placed that it either cannot be seen or will not be noticed, or by using a large source of low brightness to which users will adapt when they look at it. Modelling depends upon the spatial distribution of incident light; shadow upon the surrounding luminance field; thus if sharp shadows are required a bright source of small subtense is essential, placed out of sight. For the display of architectural features, sources may be located which illuminate them without lighting users of the interior. For example, at the Louvre in Paris projectors light bas-reliefs at glancing incidence to produce, by themselves, a very marked structure pattern; the normal diffused lighting of the room reduces this marked pattern to a pleasing level.

For directional lighting of people in the room, if shadows are desired, small bright sources can be used provided that their light is visible only at large angles of elevation. To ascertain experimentally the permissible angles, a lighting fitting was constructed having a small bright source which was visible through colour filters, the junction between different colours occurring at known angles from the downward vertical. This fitting was suspended in an interior and users were asked which colour they noticed. From this rather crude experiment it was concluded that sources of reasonable brightness can be used if they are not visible at less than about 50 deg. above the horizontal.

If sharp shadows are not wanted, modelling effects can be achieved without using small bright sources. An experiment was made in which the polyhedron apparatus was illuminated to the same level by a series of sources of subtenses varying from a very small source to one subtending nearly one steradian; it was found that the appearance of the polyhedron was almost unchanged. This points to the possibility of achieving useful modelling effects by, for example, making one wall substantially brighter than the remainder, by a suitable combination of lighting and decoration. Modelling of the interior is here clearly linked with emphasis of the wall.

Clearly, some buildings are more easily dealt with than others. The simplest conditions occur when the users do not move about, when they face all in the same direction and their centres of attention are known and obvious. The simplest of all are theatre stages, where the comfort of the actors is not a question and the audience does not go on the stage; there, and in similar places, the techniques of modelling and emphasis are already well developed. Next come churches, concert halls and the like, where also some attempts have been made. The problem is most difficult when users may be anywhere and looking anywhere—for example, shops and hotel lounges. Always we shall have to design for appropriate apparent brightness, correct emphasis and due revealing of form and texture as well as for adequacy and comfort, and only when these factors are properly balanced in a single harmonious design will a really good result have been achieved.

This is the central point. The studies here reported may help the designer to express and achieve his purpose, but they cannot provide the purpose: without a clear purpose the result is bound to be aimless. Purpose in design is a matter not of engineering but of aesthetics, and at this point the lighting engineer must come to the architect for help, since the problem is in his field. It resides not only in the lighting but in the interior as a whole, and if the purpose of the interior is vague there is little point in attempting a refined lighting effect.

The detailed studies of lighting here outlined will probably be worth while only in large and important interiors; for less elaborate rooms short cuts will doubtless suggest themselves. Probably we shall discover that if we can arrive at a clear purpose

of what we want to do, we shall quickly find ways of achieving it without undue complexity.

## Appendix I

### Definitions

The following definitions relate to terms used in this paper which are either novel, or which are used in a particular way.

*Surrounding Luminance Field.* At a point: the distribution of luminance of the light visible in all directions from that point, as a function of directions in space referred to that point. (This may relate to a point in space with reference to the formation of a texture or shadow pattern in its neighbourhood, or it may relate to an observer, with reference to the adaptation level, apparent brightness field or discomfort glare which he experiences. It may also relate to that part of the luminance field which surrounds an observer's point of regard.)

*Adaptation Level.* The luminance of a uniform luminance field, in which the sensitivity of the eye is identical with its sensitivity in a stated luminance field. (In practice this cannot yet be ascertained with accuracy, and in the work described in this paper it has been taken to be approximately the mean luminance of the field within about 10 deg. of the point of regard.)

*Apparent Brightness.* A number which is possibly a correlate of luminosity, obtained from curves due to Hopkinson[3] which relate it to the luminance field and to the adaptation level of an observer.

*Spatial Distribution of Incident Light.* At a point in space: the illumination of a small plane element of surface located at that point, expressed as a function of its orientation.

*Consistent Range.* At a point: the range of illumination of a small plane element of surface located at that point, which occurs without inversions as it rotates in a stated way. (In this paper consistent ranges refer to the values of illumination which occur when the surface is oriented in specific positions spaced usually at 45 deg. steps.)

*Azimuth Range.* The consistent range if the normal to the surface rotates in azimuth. The azimuth range in this paper relates to the rotation of the normal in azimuth while inclined to the downward vertical at 45 deg., 90 deg. or 135 deg., or to the mean of the ranges for these three elevations, as indicated.

*Altitude Range.* The consistent range if the normal to the surface rotates in a vertical plane in that azimuth for which the consistent range is a maximum.

*Modelling.* The process of revealing the form of a solid body by forming appropriate modelling patterns; the propensity of the lighting for so revealing solid objects.

*Modelling Index.* A number expressing the capacity of an incident light distribution at a point to reveal the forms of solid bodies at that point. In this paper, the consistent range, usually in azimuth.

*Modelling Pattern.* A pattern of luminance presented by a solid body, presumed matt, arising from the varying orientation of its surfaces with respect to the spatial distribution of incident light.

*Cast Shadow.* Reduction of illumination of a surface due to the interposition of some opaque body between it and some or all of its sources of illumination. (Cast shadow is not restricted to cases where the boundary of the shadow is easily perceptible.)

*Cast Shadow Pattern.* A pattern of luminance, or a modification of another pattern, due to cast shadow.

*Structure Pattern.* A pattern of luminance which is the combination of the modelling pattern and the cast shadow pattern, and by which the form of a solid matt body is portrayed.

*Texture Pattern.* A pattern of luminance presented by a solid body which is not matt, the pattern being a modification of the structure pattern and arising from the

interaction of the reflection properties of the surface of the body and its geometrical form with the surrounding luminance field and the spatial distribution of incident light. The texture pattern displays the finish of the body.

## Appendix II

### The Study of Complete Interiors

*(i) Technique*

In the course of the work described, a complete study has been made of several interiors each under several conditions of lighting. In any interior, under any one condition, the following investigations have been made :—

Record of interior, comprising plan showing furniture, positions of measurement and view with details of decorations (Munsell colours, reflection factors) windows and lighting equipment (fittings, wattages, positions).

Illumination survey at selected points on horizontal (working) plane.

Luminance survey—luminances at points marked on sketches, sometimes from several viewpoints.

Photographs from these and perhaps other viewpoints.

Modelling survey : Spatial illumination distributions at selected points in interior.

Polyhedron photographs at same points.

Photographs of wall polyhedra at selected points.

The whole of this repeated for each lighting condition.

Such an investigation calls for some hundreds of observations and a score or so photographs, and requires careful organisation. Each negative and print carries an identification code from which all the relevant information can be found at any time, and a consistent scheme of numeration was adopted, similar for all investigations, so that any observation can be identified. A set of record sheets was devised on which all observations are booked, including a diary sheet on which each move in the investigation is recorded, with any comments.

*(ii) Judging Panels*

In comparing installations, or lighting conditions, it has been usually impossible to take a judging panel to the site, and recourse has been made to judgments from photographs taken with a wide-angle lens, and carefully matched to the scene. This is at best not a satisfactory method : photographs cannot convey the impression of moving about in the interior, though if they are viewed through a collimating lens the effect is surprisingly realistic; they cannot provide the true range of luminance, and thus cannot reproduce discomfort, though some uncomfortable and distracting conditions are apparent. In particular, they cannot convey the sense of looking out of a window. With all these defects, however, the remarks of a panel judging two photographs are most instructive and are a necessary corrective to the opinions of a single investigator. Observers were given deliberately as little guidance as possible, and their remarks recorded. They were only asked questions afterwards, if their opinion on some feature was specially needed; but the fact that they had not commented upon it was noted as significant.

## Appendix III

### Installation Design for a Specified Gross Apparent Brightness Pattern

The design of an installation to achieve a given gross apparent brightness pattern seems at first sight to be a formidable undertaking. The apparently simpler problem of working out the brightness distribution for a given lighting installation and scheme of reflection factors involves complex interreflection theory, and to work such a process in reverse seems almost impossible. Fortunately, however, if it is worked in reverse a

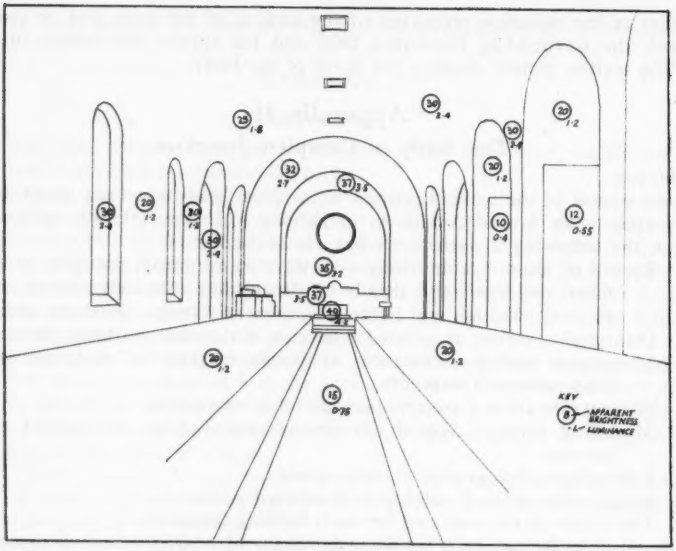



*Fig. 18. Typical specification of Apparent Brightness in interior, and corresponding luminance values.*

short cut appears to all the complexities which leads to a simple solution. It will be described by example.

In Fig. 18 a perspective view of an interior is shown which it is desired to light:

**Table 4**

**Design of Lighting Installation for Interior shown in Fig. 18**

| Point | 1<br>Apparent brightness (designed) | 2<br>Luminance (From Fig. 4) | 3<br>Reflection factor (designed) | 4<br>Total illmn. required | 5<br>Illmn. from other surfaces (estimated from luminances) | 6<br>Direct illmn. rqd. from lighting equipment |
|---|---|---|---|---|---|---|
| | | ft.-L. | | Lm./ft.$^2$ | Lm./ft.$^2$ | Lm./ft.$^2$ |
| 1 Table ... ... | 40 | 4.2 | 0.4 | 10.5 | 2 | 8.5 |
| 2 Panelling ... | 37 | 3.5 | 0.4 | 8.8 | 2 | 6.8 |
| 3 E. wall ... ... | 35 | 3.2 | 0.4 | 8 | 2 | 6 |
| 4 Chancel Arch ... | 37 | 3.5 | 0.6 | 5.8 | 3 | 2.8 |
| 5 Transept wall ... | 32 | 2.7 | 0.6 | 4.5 | 1.8 | 2.7 |
| 6 Vault, S ... | 30 | 2.4 | 0.6 | 4 | 1.8 | 2.2 |
| 7 Vault, N ... | 25 | 1.8 | 0.6 | 3 | 2 | 1.0 |
| 8 Chairs ... ... | 20 | 1.2 | 0.2 | 6 | 2 | 4 |
| 9 Carpet ... | 15 | 0.75 | 0.1 | 7.5 | 2 | 5.5* |
| Adaptation Level | 30 | 2.5 | | | | |

*Since it would be impracticable to provide a higher illumination on the carpet than on the adjacent chairs, either a lower apparent brightness should be accepted for it, or the reflection factor changed appropriately.

a church, with a simple and light-coloured interior in which pendant fittings are inappropriate.

(i) The first task is to set out a scheme of apparent brightnesses which it is desired to achieve, which must be done by experience. It is at this stage that the artistic designer expresses his conception in figures and some figures have been indicated both on the drawing, and in Table 4, col. 1.

(ii) These apparent brightnesses must be translated into luminance values. First, by inspection, estimate the apparent brightnesses corresponding to the adaptation level. A reasonable value is 30 in this case. On Fig. 4, find the intersection of a horizontal line through 30 on the apparent brightness scale with the dotted line which gives the apparent brightness of the adaptation level. From this intersection the luminance of the adaptation level is seen to be 2.5 ft.-lamberts. Using the curve for this adaptation level —which passes through the intersection already found—the apparent brightnesses selected can be translated into values of luminance; these values are shown on the drawing in brackets below the figures of apparent brightness and in Table 4, col. 2.

(iii) From the known reflection factors of the interior surfaces (col. 3), assumed matt, the total illumination required upon each is found, which will be made up partly by direct light, partly by light received from all the other surfaces. This is tabulated in Table 4, col. 4.

(iv) The contribution to the illumination of each surface from all the other surfaces can now be found, often sufficiently accurately by inspection. For each surface faces a "sky" or surrounding luminance field consisting of all the other surfaces visible from it, the luminances of which are now specified. If this field were uniform, the illumination from it would be numerically equal to its luminance in foot-lamberts; it is not uniform, but the illumination from it can be estimated by inspection probably to sufficient accuracy, from the subtenses of the various surfaces and their positions relative to the surface illuminated. For example, the illumination on the floor in Fig. 18 will come mainly from the vault, with a lesser contribution from the side walls because the angle of incidence is less; it would be reasonable to estimate 2 lm./ft.$^2$. The values for each major surface in Fig. 18 appear in col. 5. If the result is required more precisely, it can be found by treating this problem as a series of problems in daylight, for example, using a Waldram diagram.

Thus we have solved the interreflection problem without having to work it out as a complex mathematical problem, by working backwards from the required luminance distribution.

(v) The contribution required of direct light on each surface is now simply found by subtraction of col. 5 from col. 4 and is shown in col. 6. This is what is required of the lighting installation, and its further design is straightforward illuminating engineering. Many different schemes could be used as indicated in Section 7.2; their selection will be governed by considerations of modelling among others.

In the course of this calculation there may be cause to vary the reflection factor of surfaces rather than their illumination. For example, the East wall would almost certainly be too bright with practicable systems of lighting if it were as light in colour as the remainder; its reflection factor has, therefore, been reduced to 0.4, which clearly indicates the possibility of a suitable colour scheme. The above calculation has been shown for only one viewpoint and would have to be extended to cover the complete interior, with due consideration of effects in daylight, and for all important directions of view and viewpoints.

The method of calculation here outlined can be checked neatly by applying it to an integrating sphere of radius R and reflection factor $\rho$; the amount of flux required to bring about a uniform luminance B is found at once to be $4\pi R^2$. $B(1-\rho)/\rho$, which is the value given by the interreflection theory. In an interior, if the reflection factor of a surface is increased the interreflection contribution is not altered, for it is deter-

mined solely by the luminance specification and the geometry, but the illumination required on the surface to produce the required luminance diminishes; the point may be reached at which it is equal to the interreflection contribution which implies an indirect system of lighting for that surface. If the reflection factor is further increased, the luminance specification cannot be achieved, for the interreflection contribution is greater than the total illumination required for that surface.

The method of calculation here outlined for calculating for a luminance specification may also be used for designing for colour. If the final luminosity and luminance of each surface is specified, the saturation as well as the amount of light received from other surfaces at each point can be found by analogous methods. Then to achieve the required specification the additional saturation arising from direct light acting with the spectral reflection properties of the surface can be found by subtraction, so that for the light of a given hue and saturation the correct hue saturations and reflection factors of the pigments can be specified, which will in the completed interior achieve the specified luminosity and luminance.

### Acknowledgments

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## Discussion

MR. W. ROBINSON: The author has completely upset my idea of what I was going to say. I was going to raise all sorts of problems, because this is an extraordinarily difficult paper, but it has been so beautifully presented to us to-night that all the difficulties seem to have been smoothed away.

In my view Mr. Waldram has "gone to town" in this paper, for he has not only presented us with a whole mass of observational data in territory which previously was more or less unexplored, but he has penetrated that territory so far that he has been able to present us with a complete set of new definitions. He did not give us many of them to-night, but they are in the paper. I can understand nearly all of them. He has not only propounded the problem and given us the whole picture, but at the same time he has presented us with a solution, and I am sure he will agree when I say that it is a solution which has defied engineers for a very long time. Whether his solution will satisfy everyone here, I do not know; he has almost—but not quite—satisfied me.

I will not deal with the technical points of the paper, for I have not had long to read it and I shall need a lot more time with it before I can cross swords with the author, but I feel that its real importance is perhaps indicated by the rather scanty set of references at the end. They are not scanty because the author was too lazy to put

them in, but because so little work on these lines has been done previously. In other words, this paper and most of the material presented to us to-night is original.

The importance of the paper to me is that it does something for the brightness engineer. I know the author does not like that term, nor did I like brightness engineering as it was progressing, but he has given brightness engineering a new meaning and it can be said to begin from this paper. That may be going too far, because obviously the author has had the benefit of having other brightness engineers behind him in tackling this problem, but he has given a new slant to the problem and one which we ourselves can use, if not straight away, certainly in the near future. He has taken a step forward which is far greater than any step we have taken in the past.

I must express a certain doubt on one point. I should not like to feel that the paper would be treated by the Society and by engineers and architects as an academic exercise, however brilliant, or as a purely technical matter. I hope it will not be relegated to the shelf to which so many excellent and fundamental contributions to the Society have been relegated, only to be brought out again later and to be fed automatically into our lighting practice. That has happened to practically every paper dealing with fundamental problems which has been presented to this Society; their importance has been recognised 20 or 30 years later. I hope the importance of this paper will be recognised now.

Despite the presentation of the paper to-night, and despite the enormous satisfaction which it must have given all of us, it is not an easy paper. It will not be sufficient for any of us to go away inspired by what has been shown us to-night unless we are prepared to go deeper into the subject by reading the paper carefully and critically, and unless we are prepared to add our weight to it. I should like to feel that the exciting possibilities which have been raised will be appreciated by the architectural profession. I should like to feel that the architectural profession will not be left alone to go through the paper, trying to sort it out by themselves. Sometimes we overlook the fact that whereas to many of us lighting is a very large subject and occupies a lot of our time, to the architect it is only one facet of a very large job. We are apt to expect the architect to go deeper into these things because of the way we feel about them, but we must realise the difficulty of his doing so. We know the differences which arise among ourselves—the difference in outlook between the research man and the man in the field; we must similarly recognise the differences which exist between all of us and the architectural profession.

One of the great virtues of the paper lies in defining and treating the problem of lighting quality in terms which apply to the architect equally with the engineer; in that way it provides common ground between the two professions. The author has indicated quite clearly not only lines on which the architect and the lighting engineer can usefully work in co-operation but also, by implication, the absolute necessity of this co-operation if we are to arrive at a point at which the design of the visual field means what it says.

I have no regrets that the paper which I presented some time ago on brightness engineering has been rendered more or less obsolete by this paper. I am very pleased to find it so, because at that time we were wandering around in a maze. At the end of my paper I commented that the time was coming when the lighting engineer must prescribe as well as dispense the conditions for lighting; we must now extend that a little and recognise that the time has come when the architect himself must take over this job of prescribing his own lighting requirements, i.e. visual requirements for the interior. Mr. Waldram has dealt with this subject and devised a method to enable the architect to do so. That is a fundamental step. If the architect can start to prescribe good lighting, we are willing not only to prescribe when we are asked

to do so but are willing to dispense to the architect's prescription. To-night we have had an indication of how we shall do the job.

I want to raise one point of major principle, concerning the author's use of apparent brightness. He will agree that this conception is original—not to the research man, perhaps, but to the practising man. Like all original things, it might be dangerous. It must be carefully scrutinised. The whole question of the daylight factor and of absolute illumination is one of difficulty. We cannot at any stage ignore the problem of absolute brightness. We still have to see print and other small things; we have still to do the down-to-earth jobs in life. I am sure that has not been forgotten, but we must be careful not to let one aspect of lighting over-weigh another, and we must hope that much work will be done on the whole problem of the apparent brightness standard of interior lighting. It is a most important development and I am sure it will repay all the work put into it.

The author refers to the difficulty of assessing light values from photographs. I wonder whether "3-D" may help us here.

Finally, I am still not very much wiser from the definition given in the paper of what is the surrounding luminance field. Perhaps, in words of one syllable, the author can reduce this definition to one within my mental compass.

MR. R. R. HOLMES: I would like to comment on two outstanding points in this paper. The first, which Mr. Robinson has mentioned, is its importance to the practical lighting engineer. The second is the comparative simplicity of the technique of measurement suggested for obtaining ideas of modelling. It is a very complicated problem, and we must be very grateful to the author for the clarity and simplicity of the method he has suggested and used. With certain further simplifications related to the modelling index, which he did not mention, we should be quickly enabled to judge a room from that point of view; but as the author has not discussed the modelling index I will omit the comment on it which I would have made.

The reception of light at a point is a fundamental feature in every practical lighting engineer's experience. In offices, in factories, in all kinds of interiors, the plane at the point of regard is seldom horizontal, and obstruction by the body or by a machine is a factor which cannot be neglected. The author's conception of the way in which light is received at a point is one of the most important ideas in the earlier part of the paper.

In Section (3), the author comments on the poor judgment of the eye in measuring absolute brightness level. I fully endorse Mr. Robinson's remarks on the subject. The author mentioned the figure found in a certain very famous building in Westminster —5 lm./ft.$^2$—during debates, but the eye was probably a perfectly sound arbiter, because no doubt it decided what level of lighting was comfortable for *listening*. With this illumination there was probably a lack of distracting contrast in the field of view which was necessary if one was to give attention to what was being said. It also may have reduced the danger of too much altitude modelling, which might have made the general view unattractive at higher illumination levels.

In Section (4) the author gave a clear analysis of the revealing of form, and his use of the polyhedron as opposed to the sphere is very interesting. By sub-dividing his standard form into facets he made the brightness changes easily noticeable and easily measurable. The change of gradation with a matt sphere in the same position would be very gradual, but I should very much welcome photographs of a sphere or hemisphere set alongside those of the polyhedron so that we could compare the shading of a sphere, with which the architect and the artist are already familiar, with that of the form which the author employs when taking measurements.

In connection with the hemi-polyhedron, I suggest that a rather darker background

might be advisable to avoid a change in brightness due to inter-reflection near the margin, which may change the appearance.

The author has been unkind enough to accuse artificial lighting of rendering an interior "incoherent." While his comment may be justified for a bare Spartan temple, with pillars and undecorated walls, I do not for a moment think that is true of a well decorated interior to-day. Decoration, with its colours for the mouldings and doors, gives the required emphasis to the space around us, and I do not feel that we need slavishly follow daylight practice when providing artificial lighting. We must keep those freedoms which are the very essence of artificial lighting—the freedom of location and the freedom of direction. Perhaps a little more modelling in social interiors would be a good thing, but we should not necessarily follow the daylight direction every time.

The extraordinarily simple finale to the paper, in which the author arrives from the finish back at the start of his problem, is the most useful thing in such a paper which I have seen for many years.

MR. J. G. HOLMES: The author has referred to his privilege in being chairman of the sub-committee of the British National Committee which was dealing with the subject, "The Design of the Visual Field." I hope you will allow me to say that it was very stimulating indeed to have him as chairman of that committee. We had some of this paper as advance information and it contributed considerably to the value of our report. It was a very good committee, in which there were most stimulating discussions and exchange of views, and I suggest to members of this Society that in order to appreciate this paper properly they should at the same time re-read that report—if "re-read" is the right word; I hope it is—because the two taken together are perhaps more valuable than taken separately.

There is too much in the paper for the ordinary mortal to assimilate in a matter of an hour or so, even though Mr. Waldram's presentation has been very simple. One could have wished that there had been three or four papers and that each could have been discussed separately—a paper on Adaptation, a paper on Modelling, perhaps in a slightly different field a paper on Emphasis, and then, down to earth, a paper on the application of the precepts and principles which are set out in this rather long document. I hope that from Mr. Waldram or some of his colleagues there may be developments from this paper which will enable us to sub-divide it and then to assimilate it more completely.

I was particularly interested in the section on Adaptation. The I.E.S. Code gives certain precise absolute values of illumination for certain tasks. These are not minimum values; they are useful values. They are based on Weston's formula for a certain level of performance, and I believe that formula is dependent on good practice in arranging the decorations and the surrounding luminance field so that the visual task can be done in reasonable visual comfort. But it would be of very great interest to see how those illumination values can be modified, if they need to be modified, by translating them into terms of apparent brightness. I have had a go at it, using Hopkinson's 1941 results, although not very precisely. It seems to me that Weston's formula would not require much alteration, but that the level of performance for the absolute values which are recommended in the Code may be a few per cent. different from the 95 per cent. adopted for the Code. I should like to make this suggestion to the author or those working on the Code as one method of analysing and perhaps reconciling some of the small discrepancies in the present list of Code illuminations.

A comment on modelling: it was said, quite rightly, that light decorations in a room reduce modelling and dark decorations increase it. This emphasises the advantage of directional light. It is often assumed that inter-reflected light is completely uniform,

that if one were to remove the direct light without disturbing the inter-reflected light, the illumination would become almost entirely uniform. Experiment shows that that is not so and that very largely the distribution of illumination from inter-reflected light alone is more akin to the distribution of direct illumination than to uniformity. That is not to say that inter-reflected light does not reduce modelling; it does, because the distribution of direction of inter-reflected light is very much more random than the distribution of direction of direct light. It may, perhaps, be added that one of the benefits of having black or dark areas in a decoration scheme is to increase modelling as well as to give emphasis if properly used.

I have the impression that when one is working on some manual task the associated visual tasks do not require much modelling but only require illumination of a type which reveals texture and the necessary degree of detail. On the other hand, a visual task which is intended to be pleasurable requires structure modelling as well as texture and contrast.

I should like the author's comments on that difference—that the illumination for visual productive tasks is less critical of modelling than for what Mr. R. R. Holmes referred to as social occasions. A good example is the sort of photograph one sees sometimes in architectural journals. If it is intended to be a photograph of how part of a building is constructed it may be taken under an overcast sky, but if it is intended to show how beautiful the building is, then you can be sure that the photographer has waited until the sun and the clouds are in the right place, to give the right distribution of light and shadow. Another example is the use of downward light from ceiling fittings in offices and other places of work and the use of cross lighting from wall lights or floor standards in living rooms and pleasant places where azimuth modelling is specially desirable.

I welcome the remarks on the need for purpose in designing an illumination scheme. This paper helps considerably towards clear understanding of the purpose, and many technical people such as lighting engineers require to have that purpose expressed in numerical or quantitative forms, which is a difficult form of language for an architect. I was reminded a short time ago of the consternation of an illuminating engineer who was asked to design a lighting system for a restaurant so that the architect could put the building around it. The poor lighting engineer had to think for the first time of what the architect really wanted to achieve, what was the purpose of his lighting scheme, and he was in difficulties because he was not able to express that purpose in quantitative terms. I believe the author's approach will do a lot towards helping with the problem of expressing the designer's purpose in the numerical language of the engineer.

DR. W. S. STILES: Mr. Holmes's reference to the I.E.S. Lighting Code emboldens me to make a point about the notion of apparent brightness when the effectiveness of performing a visual task is in question. There is no evidence that because the task area looks brighter in the sense of apparent brightness that the facility of carrying out the task is necessarily increased. For example, if you surround a small illuminated working area with darkness, you get a slight increase in apparent brightness of the area, but in fact you do the task less well than when the surround is of the same brightness. Apparent brightness of the working area is therefore not an altogether valid guide to the effectiveness of doing the task in the area.

I was interested in the remarks which the author made about how he calculated the apparanent brightness. Unfortunately I have had time only to glance through the paper, but I gather that he worked with a 10 deg. area and ignored what was outside the area. I think that is undoubtedly the right line. Much earlier work, not only on apparent brightness but on the effects of surround brightness on just perceptible contrast, suggest that there is a quite rapid falling off in the effectiveness of the

surround zones as the angle with the working area increases, and the law of variation with angle has been determined. Working with that law one does not expect to get a very big difference between true and apparent brightness, unless the range of true brightnesses in the scene is a wide one. Taking the church lighting, which the author described in some detail, perhaps the range was a good deal wider than it would be in many interiors. Could the author tell us what difference it would have made if he had completely suppressed that part of his calculation in which he allowed for the change from true to apparent brightness, while still including inter-reflection? Also, would he agree that this was an instance where the effect of apparent brightness was greater than in many interiors and that in many interiors it would not matter very much if the difference between true and apparent brightness were ignored?

MR. K. R. ACKERMAN: I have been engaged on some work on illumination calculations and the consequent problem of inter-reflections, and in the course of it came across the same problem as Mr. Waldram, i.e., the difficulty of obtaining the size of the direct and inter-reflected components of any specified total illumination. A formula was derived from the work of Buckley, and Moon and Spenser, of such length that the average person would take about two hours to work out the inter-reflected components of illumination at each point; consequently, I think you will agree this formula would hardly be of even academic interest. It serves, however, to illustrate the complexity of a rigorous approach. I am, however, wondering whether the author has over-simplified the problem by merely averaging the brightness of all areas as seen from the point considered, whether weighted or not. Can he give some indication of the error involved in the process which has has described?

MR. G. T. WINCH: I have been particularly interested in the paper because the author has been taking into account the effects of adaptation. This touches on work which we have been doing on colour adaptation, and I should like to ask the author to what extent he feels that the inclusion of colour in the problem might modify his suggested solution. We have all seen that he has greatly simplified what some people have thought to be a very difficult problem. I am sure he will welcome colour as an added factor, and I look forward to the time when he includes it in his calculations. I feel certain that he will deal with it just as effectively.

MR. S. S. BEGGS: The greatest contribution in the paper is the link which the author has drawn between photometric brightness and apparent brightness. As Mr. Robinson pointed out, that step distinguishes the paper from all similar work which has been done before, particularly in America, where brightness engineering refers entirely to photometric measurement. I think the value here is in translating measurement into apparent brightness.

Because of that, I feel it is important for the translation to be accurate. I have not been able to decide whether the scale used is important or not. The author said he did not care whether the figures were significant or not. If they are, the figures should be accurate, and to determine the scale I think it is vital that work should be done on obtaining authentic curves relating photometric brightness to apparent brightness. I am sure Dr. Hopkinson will not mind my saying that.

If, however, the values are not important—and they may not be—it is a bad thing to use numbers. It might be better to adopt a classification of levels, for example, *a*, *b*, *c* and *d*, going in order of increasing apparent brightness. That gets rid of any inclination to assume that *c* is twice *b*. I do not know whether the author has

thought of this. Perhaps he will give an indication of whether he thinks the values are really significant and, if not, whether a classification would do.

The author is a very experienced daylight engineer, and I agree that to those skilled in this art the calculation which he has described presents no difficulty. The last thing one wants is a complex formula for determining the illuminaion; but whilst those who are skilled can estimate what will be the contribution to the illumination provided by the gross brightness pattern, to the unskilled it will be quite a difficult problem.

There is another factor which makes the procedure difficult. Having decided the brightness pattern, in order to determine the illumination you have to provide, you need to know the reflection characteristics of the surfaces. The author said the illumination is calculated from the reflection factor, but whilst that is very easy if the reflection is diffuse, with most materials you have preferential reflection. You therefore have to know the reflectivity corresponding to the direction of view and the direction of the light concerned, which complicates the translation for all normal practice.

MR. JOHN REID: Architects have been mentioned several times to-night and, as an architect, I should like to welcome the paper as a positive step towards ground where I can meet the lighting engineer and discuss with him the character of the light I want. This is in contrast to being offered a mythical 15 lm./ft.$^2$, for example, which may make the visual task possible but which is in no way related to the atmosphere or the character of the building I am trying to produce. The paper therefore seems to me to be a very valuable contribution.

There is one thing which worries me. The author glossed over it in his presentation, although I admit I have not seen the written version. It is the question of colour mentioned by one of the previous speakers. Particularly with contemporary design, in which we use strong, bright colours, the balance could be upset if we were not careful, and I should like to know what work the author is doing on the modification of his system by colour.

MR. S. HUBBOLD: I am a fittings designer—I do not call myself an illuminating engineer as such. In the past I have often envied you illuminating engineers, because all you seemed to have to do was to take the plan of a building, divide it into squares and put a lighting point at each of the intersections. If this paper will give illuminating engineers a little more work, I shall be very pleased.

In the past, when the illuminating engineer has had a difficult problem he has brought it to me to produce some sort of special fitting. I hope the engineer will not in future come to me and say, "I want a fitting designed to give me 15 ft.-lamberts in this direction, 12 in this and so on." If he does, I shall give him a sphere and lots of bits of sticky paper and let him solve the problem himself!

MR. J. C. LOWSON (Contributed): The proposed new method of interior lighting design based on apparent brightness distribution is intriguing, but the details given in the paper are somewhat tantalising in that they pass so quickly over certain of the practical points. For instance, I should very much like to know exactly how "the artistic designer" (the architect?) is to prepare his gross apparent brightness pattern in the first place. Whilst the architect can (and frequently does) express his concept by preparing a wash drawing of the proposed interior as he imagines it, the translation of this "artist's impression" into numerical terms is quite another matter. Who is to do this, and how?

I should also very much like to have further information on how to select the

adaptation level one should use when making use of Fig. 4. In view of the author's remarks concerning the rapidity with which this key quantity changes (Sect. 3.2.), its practical estimation seems likely to present rather more difficulty than the example quoted in Appendix III would appear to suggest. Certainly, the selection "by inspection" of a single representative figure may be good enough in this particular instance, since the luminance ratio is substantially within the celebrated 3 : 1 range. But very often a much greater diversity is unavoidable—and desirable. In such cases, the translation of apparent brightness into luminance, and vice versa, seems likely to be anything but straightforward.

I do not wish to suggest, though, that it is not worth trying to do it. I have long admired the elegant and instructive set of curves contained in the 1941 paper published by Hopkinson, Stevens, and the present author. The presentation of that chart in the new convenient form illustrated in Fig. 4 should certainly be welcomed heartily by all lighting men who take an interest in fundamentals. Provided that the problem of predicting the appropriate adaptation level can be satisfactorily solved, the application of this chart to everyday work should certainly help to clear up a number of difficulties. One matter which might well be examined from this angle is the problem of deciding how much artificial lighting should be used when it is necessary to supplement daylight; for instance, in parts of a large office remote from the windows.

MR. WALDRAM (in reply): I have to thank Mr. Robinson for many kind remarks, which I appreciated; I agree with most of his comments. He mentioned that the references were scanty; the paper relies upon the report, which is referred to, where there is an exhaustive list which there was no need to repeat.

Mr. Robinson made two points, which I would emphasise. First, that we needed to re-read the paper critically and to try out the ideas which it contains. I hope we all do that, because much of this is new ground. Indeed, the method of calculation given at the end occurred to me after I had submitted the paper, and it was included at the last minute. I have not yet had a chance of trying out many things which have been suggested in the discussion, because the whole conception is new.

Both Mr. Robinson and Mr. Reid spoke of collaboration with the architectural profession. We have very often talked about it, have often tried it, and have often found it fruitless because we talk different languages. If I understand the architect's position correctly his job is to conceive the building as a whole, not necessarily understanding the complexities and details of every part: I believe that he does not design, for example, his own steelwork or his own lifts. He has to understand sufficient of these things to be able to specify satisfactorily, and then he turns to the experts to collaborate with him in working out the details. It is in this way, I feel, that the method here outlined might have some virtues in making possible better contact between us.

The only thing we have given by way of complexity is one scale which I think may be fairly easy to use. But it is a new scale, and all new things need practice. The value of the scale of apparent brightness can be learned only through practical application, and I suggest that that is what we should do.

Mr. Robinson and others have drawn attention to the importance of scrutinising the figures of apparent brightness, and both he and Mr. Holmes referred to their bearing upon the Code. I have not had time to investigate this, but I look forward to doing so. From the few examples in which I have worked it out it seems to me that if you specify the apparent brightness appropriate for the job you will finish with the illumination appropriate for the job; if apparent brightness works, that should automatically function. In the drawing office of Figs. 2 and 3 the drawing-boards had the same apparent brightness by day and by night and both were satisfactory, but the illuminations were

quite different because the brightness distributions were different, altering the adaptation level. We might find that the notion of apparent brightness will simplify our approach to the problems of the Code, and perhaps to other matters.

Mr. R. Holmes said that in the House of Commons the eye was probably a sound arbiter. I think the eye is a sound and the only arbiter; when we find that we are getting figures which do not agree with what the eye tells us, it is time to think again. That is the tenor of the paper.

Mr. Beggs queried the use of numbers for apparent brightness, and referred to my remarks about its basis. I think that numbers are justified rather than letters, for apparent brightness seems to be a scalar quantity. The numbers we use may not be a linear function of apparent brightness; that we may never establish. I am only concerned to find numbers which will express experience consistently—so that brightnesses which appear equal are expressed by the same number, and that the numbers expressing apparently unequal brightness are always in an order consistent with experience. If such a scale can be found, its basis is immaterial and may be arbitrary so far as the illuminating engineer is concerned. Linearity is unimportant as we do no arithmetic with the numbers.

Mr. Holmes also referred to the polyhedron and the sphere as standard structures to gauge modelling. I found a sphere far too delicate an indicator; the polyhedron turned out to be a more useful guide. It has been suggested that inter-reflection back to the polyhedron from the background might be important, but we have not found it so. The background is useful in indicating shadow. We made paper hemi-polyhedra which were stuck to the walls and photographed them from a range of a few feet; this gave a useful record of conditions at the wall as to both modelling and shadow.

It has been suggested that I said artificial lighting made an interior incoherent. I did not say it made the interior incoherent; I said the directions of light were incoherent. This was pointed out in 1920 in a paper by John Darch, an old member of the Society. In an interior which relies very much on colour for its design you will not make an interior look incoherent, but the directional effects throughout the interior are usually incoherent by artificial light.

I did not intend to imply what Mr. Holmes seems to fear, that in designing interiors we should slavishly follow daylight. In designing the lighting for the church which I showed, we did not; we took the outline of the church interior and asked ourselves, " How should we like this to look ? "* By luck, daylight gives some beautiful lighting sometimes, but it can give some appalling lighting. When we have the whole field open to us and all the advantages of the modern techniques of artificial lighting, we are not so limited; let us go to our architect friends and ask them to help us. That is the point which I stressed. We have to appeal to the architect for help in settling the purpose of the design. I do not believe many illuminating engineers can do it themselves; if there are any who can, that is splendid, but we want far more, and in the meantime we have to go to the architect.

Mr. J. G. Holmes said there should have been three or four papers, but there were practical objections to that course. I was intrigued by his suggestion that work does not call for good modelling, but that a pleasurable view does. Does this not depend very much on the work ? A very simple task, like shovelling coal, does not call for nice lighting, but for critical types of work, particularly on polished surfaces, or on textiles, a nice design of lighting may be very important, as is recognised in industrial lighting design by those skilled in that art.

Dr. Stiles challenged me on exactly how I worked out the adaptation level. Frankly, it was an estimate, and it was very rough indeed; but this may be justified, at least at the beginning. We start with aesthetic judgment and finish with a lighting design with practical equipment, and neither process can possibly be precise. There

* NOTE.—In presenting the paper a different example was used from that given in the text, and a photograph was shown of a trial installation realising the designed appearance.

is great interest from the physiological point of view in knowing what we mean by apparent brightness and how far it works but, restricting ourselves to the business of the lighting designer, I think we can get away with a lot of approximation and still get the result we want, nearly enough for our purpose. That is sound engineering, because surely the engineer is the man who knows how, when and where to approximate. That is not an answer to Dr. Stiles, and my reason for not giving him one is that I do not know what it is.

He asked whether it was possible to design in luminance instead of in apparent brightness. The method of design outlined in the paper can be used for either; the point is rather the skill with which the designer can specify his requirements directly in luminance without allowing for adaptation. Bearing in mind all the anomalies to which I have referred early in the paper, I feel on more sure ground with apparent brightness than with well-tried but mendacious luminance.

Mr. Winch referred to colour adaptation. I have done very little work on that, but there is a problem of inter-reflection in it which I think every decorator knows, particularly those who do decoration at home. Frequently what looks excellent on a colour card looks bad in the room, because it is too saturated. Saturation of colours is considerably altered by inter-reflection, and it has been possible to work out a simple chart which indicates how much to dilute the paint, given information of how much light is reaching it after reflection from paint of that colour. At the moment, unfortunately, it works only where there is one colour. I agree with Mr. Winch and Mr. Reid that colour is an enormous field which I have left out of the paper.

Mr. Beggs referred to the calculation of inter-reflection by inspection. Perhaps I have an advantage there, but it is not a difficult problem and I hope that the B.R.S. protractors and other devices known to the daylighting engineer will be called in to help. We must learn to use each other's techniques and treat the matter in an engineering way. Mr. Beggs referred to surfaces which are not matt. Calculation for a preferentially reflecting surface would be very difficult; but fortunately, although we meet these surfaces in interiors, it is mostly on details such as furniture. Sometimes it is necessary in commercial buildings to use glossy paint, and the result is glinting reflections everywhere, which could not be predicted. Wherever possible, a matt or eggshell finish is used on major surfaces to avoid those reflections.

In reply to Mr. Hubbold, I hope we shall get away from the practice of putting a fitting in every square of the ceiling. It is often bad practice—it has been called "space pollution"—and it leads to lack of modelling. We may still go to Mr. Hubbold for some special fittings, however; perhaps something can be done with fittings with adaptable distributions.

The reply to Mr. Lowson is partly contained in the reply to the discussion. The translation of the architect's conception with figures of apparent brightness will have to be done by the architect and illuminating engineer in collaboration, aided by the examples shown in the scale of Fig. 4 and by experience as it accumulates. I am for example, making a collection of photographs of interiors, with apparent brightness indicated, as a help in specifying, and some of them appear in the printed paper.

The estimation of apparent brightness is partly dealt with in my reply to Dr. Stiles. It has proved most difficult when the brightness range is very great, as for example in daylight. But when one is *specifying* the brightness in an artificially lighted interior, such great ranges are unlikely to be met. I agree that there is much to be learned about apparent brightness, but we shall not learn much unless we make a start using estimates, even though approximate, to begin with.

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